Chapter 6

Non-potential Features of the Magnetic Field [1]

6.1 Introduction

It is well accepted that solar flares are powered by the energy stored in non-potential magnetic field of active regions. From the observational point of view, studies of the non-potentiality of solar magnetic fields contain following three aspects:

1. to find appropriate descriptions of the non-potentiality, such as angular shear, source field, vertical electric current, force-free factor (or the normalized current helicity), etc.

2. to establish the detailed spatial and temporal relationship between flare occurrence and the nonpotential characteristics.

3. to clarify the generation and development of the non-potentiality of ARs,

which are essential for us to understand the physics of solar flares and other dynamic phenomena as well.

6.1.1 Magnetic Shear

A substantial signature of non-potentiality is magnetic shear, which was first recognized from the morphology of Hα fibrils or filaments in alignment with the magnetic neutral line (Zirin & Tanaka 1973). Direct confirmation of magnetic shear at the photospheric level comes from vector magnetic field observations. The azimuthal difference between the observed field and the calculated potential field is a measure of the degree of magnetic shear (Hagyard et al. 1984). The extension to this definition includes two improved descriptions: the weighted shear angle with the transverse field strength (Hagyard 1990) and the shear angle of the vector magnetic field (L$\ddot{u}$ et al. 1993); one of the advantages for the latter description is its direct correspondence to the nonpotential field and to the magnetic energy stored in the nonpotential magnetic field (Wang et al. 1996).

Since the two-dimensional angular shear representation was introduced by Hagyard et al. (1984), many studies have confirmed the discovery of a close spatial correlation between flares and sites of strong magnetic shear around the magnetic neutral line (Hagyard & Rebin 1986; Moore, Hagyard & Davis 1987; Hagyard 1990), but in some observations, the flares were found taking place not at the region of the maximum shear (Fontenla et al. 1995; Wang et al. 1996), giving the opposite cases of an sufficient condition for flare to occur (Hagyard 1990). In the studies of flare-associated changes in the magnetic field, some results show that magnetic shear so-defined increases before flare onset and relaxed after the flare, as implied by most magnetic models (Krall et al. 1982; L$\ddot{u}$ et al. 1993), while some others show the increase of magnetic shear during the flares (Hagyard et al. 1993; Ambastha et al. 1993; H.M. Wang et al. 1994; Chen et al. 1994; Zhang et al.

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1994). For this contradiction, it has still not a definite explanation, which may be due to limitations of magnetic measurement in spatial or temporal resolution at present, or due to the photospheric dynamic precesses, e.g. drastic vortical motions or flux emergence. It is also possibly due to the scenario that the flares powered in the corona relax the stressed magnetic field through changing a global field topological configuration, so locally lead to the decrease or increase of angular shear in the photospheric boundary.

Much work has been done with regard to shear generation to date. In observations, the formation of flare-related shear has been associated with flux emergence (Zirin 1983), flux submergence (Rabin, Moore, & Hagyard 1984), flux cancellation (Martin, Livi, & Wang 1985) and vortical motions in an emerging flux region (EFR) (Martres et al. 1982). Based on the high resolution Hα observations, Kurokawa (1991) addressed in particular two distinct types of shear development: (a) collision of two sunspots of opposite magnetic polarities (Gaizauskas & Harvey 1986; Kurokawa 1987; Gaizauskas, Harvey, & Proulx 1994), (b) successive emergence of twisted magnetic flux loops (Kurakawa 1987, 1989, 1991; Tanaka 1991; Wang et al. 1991; Wang & Tang 1993; Tang & Wang 1993; Zirin & Wang 1993). In view of the magnetic environment of the EFRs, Wang (1994) further divided the scenario of shear development into four modes: (1) satellite dipole intrusion; (2) collision of different dipole; (3) flux emergence in great δ-sunspots; (4) flux emergence in an active center (Bamba 1987). All four modes can be incorporated in Kurokawa's two types of shear development. From the physical point of view, magnetic shear is either generated by local dynamo effect, or by the upward transport of magnetic shear from a subphotospheric layer (Wang 1994).

6.1.2 Electric Current System

Electric current systems are a key component in understanding magnetic non-potentiality of ARs. In the upper chromosphere and lower corona, configurations containing magnetic free energy are characterized by distorted field lines and the presence of field-aligned electric currents, which drive much of the variation of solar activity. The large-scale current systems are also believed to be the source of coronal heating (Tucker 1973; Rosner et al. 1978; Mikic, Schnack & Van Hoven 1989; Metcalf et al. 1994), as evidenced by X-ray bright structures. Furthermore, the general analysis of the electric current systems can discriminate between contending theoretical models.

Electric current cannot be measured directly in the solar atmosphere. They can be only derived from measurements of the vector magnetic fields by Ampere's law. Some numerical methods for the vertical current calculation have been introduced in Sect. 3.3. These calculations are limited to sunspots and to their near surroundings where the transverse magnetic field strength can be measured with sufficient accuracy, but the very obstacle is the problem of solving the 180^o ambiguity of the transverse field measurements, which has been discussed in Sect. 3.2.

Different flare models predict the possible distinct morphological relationship between flare sites and active region currents. This, in turn, may help us from observations to identify which mechanism actually works in solar flares. In the earlier work, the discovery of the initial flare brightenings in Hα corresponding with the current peaks (Moreton & Severny 1968; Klmn 1978; Hagyard, West, & Smith 1984; Lin & Gaizauskas 1987) supported the current-interruption models (Alfvén & Carlqvist 1967; Smith & Priest 1972; Spicer 1981). However, more recent results indicate that most Hα or Hβ flare kernels do not coincide with the peaks of vertical current (Romanov & Tsap 1990; Lin et al. 1993;

Wang, Xu, & Zhang 1994; Fontenla et al. 1995; Wang et al. 1996). Using Hα imaging spectroscopy, Canfield and his co-workers identified the chromospheric sites of intense nonthermal electron precipitation in the impulse phase of the flares, and also found that the precipitation tended to occur near the current concentrations (Canfield et al. 1993; Leak et al. 1993; de La Beaujardire et al. 1993). These observations suggest that erupting-filament models (Kopp & Pneuman 1976; Sturrock 1989; Masuda 1993), or the interaction of current-carrying loops (Sweet 1958; Gold & Hoyle 1960; Tajima et al. 1982; Sakai 1993) may be relevant in the flares. Such scenarios were also confirmed in the morphological analysis of SXR images from *Yohkoh* observations (Kurokawa et al. 1992; Akioka et al. 1993; Hanaoka 1996). In these scenarios, the initial flare signature is not co-spatial with photospheric vertical currents simply because the field is not vertical at these sites, if the region is force free.

Two mechanisms have been proposed to explain generation of vertical electric currents in the photosphere. One is the motion of local magnetic plasma, which leads to the appearance of twisted field lines (Tanaka & Nakagawa 1973; Krall et al. 1982; Hofmann & Kalman 1991; Schmieder et al. 1994). The other is the emergence of electric current systems from the sub-photosphere (Kurokawa 1987; Sturrock 1987; McClymont & Fisher 1989; Tanaka 1991); in this case, magnetic bipoles closely related to EFRs are observed carrying electric current when born (Wang, Xu, & Zhang 1994; Zhang 1995; Leka et al. 1996).

6.1.3 Spatial Field Configuration

More studies have confirmed the close relationship between flare activities and the non-potential characters like magnetic shear and vertical electric current in the photosphere, but the accurate sites of flare occurring and flare-associated changes of these features are sometimes observed inconsistent with those expected by models. This implies that a comprehensive interpretation of such relationships and the mechanisms of energy release requires the knowledge to the spatial structure of the preflare coronal magnetic field (Priest 1981; Machado et al. 1988). But unfortunately the magnetic field is not yet observationally accessible in the tenuous and hot plasma that fills the corona (see Sakurai 1989; Amari & Démoulin 1992, and references therein). Instead, 3-D structure of the coronal magnetic field has been reconstructed from boundary data measured at the photosphere, under some reasonable assumptions about the physical state of the corona. Although this strategy looks rather straightforward, many problems have been encountered since the early attempts of Schmidt (1964). The recent reviews of the so-called reconstruction problem are given by McClymont, Jiao & Mikic (1997) and Amari et al. (1997).

On the other hand, the coaligned multi-waveband observations also offer an indirect way to access the spatial field configuration of ARs. Because magnetic forces dominate over others in the upper atmosphere, abundant of spatial field structures can be inferred from the bright structure and hot loops in soft X-ray images (e.g. Craig, McClymont, & Underwood 1978; Metcalf & Fisher 1996). In a previous work (Qiu et al. 1997), we have studied in detail a flare event in AR7321, observed in chromospheric and coronal emissions, and investigated the thermal and nonthermal features involved in this event. Such study of the coordinated data from chromosphere to the corona, with very high spatial and temporal resolutions to date, also provides the opportunity to explore the possibility to recover the magnetic configuration where the flare occurred and was fueled. Our interest in this active region also lies in the fact that it is a typical EFR, where strong

emerging flux pronouncedly changed the magnetic field from a simple dipole structure into a complex nonpotential field configuration with multiple magnetic loops (Liu et al. 1998; Wang, Qiu, & Wang 1998).

In the following, we first describe the evolution of the vector magnetic field and vertical current system, then compare these features with the flare morphology in Hβ and SXR. Finally we discuss the scenario of the flare in the light of the understanding on the configuration obtained.

6.2 Observations

6.2.1 Active Region NOAA 7321

The active region NOAA7321 was an emerging flux region (EFR), which was born on October 24, 1992 and disappeared from the western limb on November 2. During the few days, it underwent a continuous change in configuration and frequent flares haunted this region. Preliminary studies on the magnetic features and flares in this active region have been published (Kawakami 1993; Takakura et al. 1994; Zhang 1995) and in the present paper we will investigate in detail the evolution of the magnetic configuration from October 26 to October 27 as a clue to the interpretation of the 1N/M1.1 flare at 01:44UT on October 27.

The flare at 01:44UT on October 27 was observed by the H_α spectrometer in the solar tower in Nanjing University and the *Yohkoh* instruments SXT, HXT and BCS. The flare underwent the onset, impulsive phase and the decaying phase, evolving rapidly within half an hour. It was made up of a low-lying, compact flaring loop with its two feet emitting intensely in both HXR and H_α bands, and some other coronal bright structures (loops). The analysis of the coordinated observations was done by Qiu et al. (1997). In section 6.5 and 6.6, we will refer to some of the main results in Qiu et al (1997) for further investigation in this paper.

For this active region, a series of photospheric vector magnetograms (FeI 5324.19$\AA$) and H_β filtergrams (4861.34$\AA$) were taken by the Solar Magnetic Field Telescope (SMFT) in Huairou Solar Observing Station (HSOS), Beijing Astronomical Observatory. The field of view is $5'.23 \times 3'.63$, and the angular resolution is around $2'' \times 2''$. The noise level of the line-of-sight magnetograms is < 25G, while for the transverse magnetograms, it is less than 190G, estimated from the average value of the transverse field strength in areas far away from flux concentrations in the active region. The 180^o ambiguity in the transverse field is resolved by using the empirical method in a multistep procedure (Canfield et al. 1993; Wang 1994).

6.2.2 Evolution of Magnetic Configuration

From Oct. 26 to Oct. 27, considerable changes were taking place in the magnetic configuration, which was characterized by the emerging flux and the motions of spots. Two vector magnetograms on Oct. 26 and 27 are compared in Fig.6.1; the latter was taken just before the onset of the 01:44UT flare. Seen in the figure, the major spots N and S were present and made the main poles in the active region. East to the N spot, a group of satellite spots made up the S2 polarity. The inversion line of the line-of-sight field is drawn. For convenience, we name the segment of the neutral line that separates N from S as *nl1* and the segment separating N from S2 as *nl2*.

On Oct. 26 (Fig.6.1a), due to the emerging flux along the neutral line, the nonpotential feature was already strong in the active region, manifested by the inversion-line-aligned transverse field. The shear angle thus defined by Hagyard et al. (1984) was 90^o along both *nl1* and *nl2*. The alignment of transverse field lines also defines the magnetic connectivity in this region, which was clearly divided into two patterns by *nl1*. The first pattern, labeled as L1 in Fig.6.1a, connected the minor spots of N1 and S1 and the second pattern L2 connected N$'$ with S2. It is distinctive that emerging flux along the neutral line made up the connectivity patterns in this region. The connectivity patterns shown in Fig.6.1 are plotted by tracing the vector of transverse field lines. They can be supposed as magnetic loops projected into the photosphere (Liu et al. 1997; Wang et al. 1997), which, in section 6.3, will be further confirmed by the comparison with the flare configuration in multi-waveband observations.

The emerging flux system was fully developed on Oct. 27 (Fig.6.1b). Compared with the magnetogram taken one day before, several new spots, N3, S3, and S4 were found appeared, and N1 were enhanced evidently. Emerging magnetic structures brought in new connectivity patterns as well. Seen in Fig.6.1b, the transverse field alignment along *nl1* was changed, indicating a new pattern of L3 (drawn by hand in thick white lines in the figure), which connected N3 with S3. Noteworthily, such pattern of the strong shear, demonstrated by the unanimously inversion-line-aligned transverse field lines, may suggest that the strongly sheared zone along *nl1* be the interface between the two magnetic patterns, namely, loops L3 and L1, or the photospheric intersection of the separatrix at the boundary of the δ-structure due to the emergence of L3. Similar conclusion applies to the zone along *nl2* as well. With the emergence of L3, the shape of *nl1* was different from one day before and the spots N and N1 were pushed southwest. As a result, L1 was twisted and the main spot N rotated clockwisely by an angle of about 20^o. For the pattern L2, not much change was taking place and the magnetic shear here remained high, but the spots of S2 group showed a running-away motion. Besides, between N1 and S4, yet another pattern L4 was formed, which was not seen one day before.

6.2.3 Evolution of the Vertical Current System

6.2.3.1 Distribution of Vertical Current

The nonpotential feature of the magnetic field, specificly, the strong shear of transverse field along the neutral line, implies that the active region could well be a current-carrying system, which was formed by emerging flux and spots motions. In this section, we will examine the evolution of the major vertical current channels (regions of high vertical current density), or the footpoints of atmospheric currents in the emerging field configuration, from October 26 to October 27.

In order to calculate the vertical current, we first pretreat the transverse field data with a Fourier lowpass filter. This method is proved efficient for minimizing the high-frequency measurement noises without losing the major structures in the field (Wang et al. 1997). Hence the vertical current can be readily deduced with the differencing method and the accuracy of such calculation is directly determined by the resolution of the filter. For our data, we obtain the filtering resolution as about $11''\times7''$, when the relative cutoff frequency, $\bar{k}_c$, is given as 15. The major vertical current channels can be illustrated in this resolution (Fig.6.2) and the noise level in the vertical current is estimated from the standard deviation of currents measured in areas where the transverse field is weak (Canfield et al. 1993).

Figure 6.2 shows the vertical current density distributions in gray-scale maps with the contours of the line-of-sight magnetograms superposed on. The cutoff frequency of the filter for the corresponding transverse fields is taken as 15 and the vertical currents above the $2\sigma_J$ level (σ_J is the noise level of current) are drawn in the maps. The current upflowing from the photosphere (the positive footpoint) is shown in bright colors, while that downflowing into the photosphere (the negative footpoint) is shown in dark colors.

Table 6-1 Parameters of the vertical current distribution

		Oct.26			Oct.27	
Cutoff of current density J_c	σ_J	$2\sigma_J$	$3\sigma_J$	σ_J	$2\sigma_J$	$3\sigma_J$
Positive total current I^+ (10^{13}A)	2.34	1.52	1.18	3.59	2.01	1.43
Negative total current I^- (10^{13}A)	2.35	1.51	1.13	3.55	1.91	1.15
Current imbalance measurement $\Delta I/\bar{I}$ (%)	−0.31	0.22	4.4	1.0	5.0	22.
Nosie level of current σ_J (mA/m^2)		1.3			2.4	
Minimum current density J_{min} (mA/m^2)		−19			−23	
Maximum current density J_{max} (mA/m^2)		34			35	

In order to check the balance between the upflowing and downflowing currents, in Table 6-1, we list and compare the total positive/negative vertical current I^+/I^- calculated at different current cutoff levels ($J_c=\sigma_J$, $2\sigma_J$, and $3\sigma_J$). The minimum and maximum vertical current densities J_{min} and J_{max} are also given in Table 6-1. From the imbalance measurement $\Delta I/\bar{I}$ (defined as $2(I^+-I^-)/(I^++I^-)$), it is seen that the total currents are basicly balanced when the cutoff J_c is taken as σ_J, or $2\sigma_J$, whereas the upflowing current dominates in the active region when the cutoff is taken as $3\sigma_J$; this is especially true on October 27, when the imbalance measurement exceeds 22%. This can be understood with respect to the the fact that the upflowing current is strong and concentrated, while the downflowing current is relatively weak and disperse, and this trend becomes more obvious on October 27. The distinct imbalance of the total currents at $3\sigma_J$ level also means that this selection of the current cutoff value is probably unsuitable for this active region.

6.2.3.2 Evolution of the Vertical Current System

On October 26 (Fig.6.2a), the pair of current footpoints J_1^+ and J_{11}^--J_{12}^- were just located along the zone of the emerging pattern L1, and J_1^+, J_{12}^- were cospatial with the emerging poles N1 and S1, implying that L1 might be a current-carrying pattern. Similarly, the dominant current pair J_2^+ and J_2^- were also located in the area where the dominant emerging pattern L2 was present and the maximum of positive current footpoint J_2^+ was cospatial with the pole N2, the most drastic emerging feature on this day.

On October 27 (Fig.6.2b), the total currents increased with the enhancement of the emerging poles. The current pair J_1^+-J_1^- became significant. The positive footpoint J_1^+ extended to a larger area and its maximum turned to be associated with the newly emerging pole N3; on the other hand, the negative footpoints J_{11}^--J_{12}^- corporated into a compact footpoint J_1^-, which was associated with the enhanced pole S1 and the new pole S3. Due to the motions of the dominant emerging poles, there was some change in the morphology of the current pair J_2^+-J_2^-. In addition, it is noteworthy that the sections *nl1* and *nl2* of the magnetic neutral line were nearly coincident with the reverse lines of the vertical currents, and the vertical current density bore a strong gradient on both sides of the current reverse lines.

The analysis of the vertical current system reveals the following features in its evolution: (1)the major current pairs are associated with the dominant emerging patterns;

(2)the peak of the current footpoints appears to be nearly located in the areas with the most drasticly emerging poles; and (3)the sections of the magnetic neutral line are coaligned with the current reverse lines, where there is a strong vertical current gradient and perhaps the horizontal current.

6.3 Field Configuration of a 1N/M1.1 Flare

6.3.1 Spatial Correlation between the Flare and Magnetic Loops

The 1N/M1.1 flare occurred at 01:44UT on October 27. A comprehensive study of the coordinated observations of the event was given in Qiu et al. (1997). From the observations, the configuration of the flare from the low chromosphere up to the corona can be established, which may serve as a means to investigate the magnetic configuration in the space. Figure 6.3 gives the coaligned observations of the flare in SXR and H_β images, superposed on the photospheric magnetogram taken on Oct. 27. The magnetic connection patterns are drawn in the figures and are found well identified with the flare regions.

A compact flaring loop (loop AB) is prominently shown in the SXR images and coaligned with the pattern L3, which emerged on this day along the magnetic neutral line *nl1*. At the onset of the flare (Fig.6.3a), three bright locus in SXR emission along this pattern seem to indicate the two emitting ends (A and B), or feet, and the bright top (D) of the L3 loop. Similarly, the magnetic connection pattern L2 finds its coronal counterpart in well coaligned SXR emission streak, which runs across the neutral line *nl2* and heads into an extended foot area (region C) in S2 region. The coalignment seen for this pattern also suggests that possibly L2 and L3 share a common foot which is foot A. For the pattern L1, the alignment of SXR emission even portrays the feature of the twist along this loop, which is rooted in E and F and seems to interact with the shorter loop L3 at the site of D. This point will be discussed in more details in section 6.3.3. The coalignment in L4 just gives the last example in this comparison.

For all patterns, H_β emission is located at the ends of SXR streaks, or the footpoints of the loops in the chromosphere (seen in Fig.6.3b). The above coordination is a comparison of the projections of the magnetic loop structure in the photosphere, chromosphere and corona, which offers an indirect way to view vividly the spatial configuration of the magnetic field, specifically, the magnetic structures associated with the energy storing, releasing or depositing sites where flares are produced.

6.3.2 Vertical Current System and Flares

In Fig.6.4, we further demonstrate the spatial relationship between the flare regions and the vertical current distribution on October 27 when the flare occurred. It is seen that the feet of the flaring loop L3 in SXR are located immediately on the two sides of the current reverse line, which is virtually coaligned with the magnetic inversion line here (*nl1*) (seen in Fig.6.4a). One foot (A) is found just at the edge of the strong current concentration J_1^+ and the other (B) is almost above the reverse line of a current pair. However, the emergence of this bipole is continuously accompanied by the input of magnetic complexity (eg., the strong shear) from below the photosphere, and the existence of horizontal current inside the loop L3 cannot be excluded.

The flaring loop L1 travels from the positive current concentration to the negative one, connecting the current pair of J_1^+-J_1^-, and the two feet E and F are well coaligned with it;

one foot (E) is exactly located in the vertical current maximum of J_1^-, while the other one (F) is in between the maxima of two current concentrations J_1^+ and J_2^+ (seen in Fig.6.4b). Since the magnetic field in the chromosphere and corona is generally regarded free from force (Metcalf et al. 1995), the pattern L1, given its long expanse, can be well extending to the corona and carrying the field- aligned current whose footpoints are perched in the photosphere. The pattern L2 also straddles the the vertical current reverse line around *nl2* from J_1^+ to J_2^-, but the site of C is not a region of strong current concentration.

The above comparison offers the information that the flare may originate from the instability at the interface between two current carrying loops, one being the pre-existing loop L1, and the other being the newly emerging and strongly sheared loop L3, which, on the one hand, considerably enhanced the complexity of the field along *nl1* and pushes loop L1 into a twisting structure, and on the other hand, interacts with the overlying loop L1 at certain critical site.

6.3.3 Scenario of the 1N/M1.1 Flare

Seen from Fig.6.3a and Fig.6.4a, at the onset of the flare, three bright regions were lying in the SXR emission streak along L3, among which, the feet regions A and B were further enhanced in the impulsive phase (Fig.6.3b and Fig.6.4b) and actually became the nonthermal electron depositing sites giving strong HXR and chromospheric features (Qiu et al. 1997), while the region D, or the top of loop L3, faded in the impulsive phase. The morphological comparison carried out in the previous sections seem to suggest that the interaction between L1 and L3 may occur at the site of D. Indeed, in Qiu et al. (1997), we have spotted a hot component of the coronal plasma and found that both thermal and nonthermal processes were taking place at the very onset of the flare; the HXR images synthesized from *Yohkoh* observation also reveal a loop top source at this time (Takakura et al. 1994). Combining the above facts, we are able to establish the following scenario of the initial phase of the flare: the flare was triggered by the interaction between two current-carrying loops at the top of loop L3 where the *in situ* energy release occurred through the rapidly heated plasma and energized electrons.

However, one minute after the onset, the flare was greatly fueled in the impulsive phase, which cannot be viewed as simply a secondary effect of the initial energy release at the loop top. Strong SXR emission was concentrated in regions A and B (Fig.6.3b and Fig.6.4b) and so was the nonthermal HXR emission (Qiu et al. 1997). In fact, even at the onset of the flare, these two regions were already favored by the energization process. We should further explore the physics in this loop.

Figure 6.5 illustrates the SXR flare at the onset of the event superposed on the map of free energy distribution. The free energy is calculated as the following:

$$\rho_{free} = \frac{B_s^2}{8\pi} \tag{6.1}$$

where B_s is the source field (Hagyard, Low, & Tandberg-Hanssen 1981), or the departure of the observed vector field B_o from the potential field B_p deduced from the observed longitudinal field, B_s=B_o-B_p, which contains information on the path of atmospheric currents whose footpoints on the photosphere are mapped by vertical currents (Moreten & Severny 1968; Hagyard 1988; Wang et al. 1996)

It is seen that the flaring loop L3 is where the free energy gets most concentrated and the regions A, B and D are coaligned with the energy density maxima. To be more careful, since the loop L1 and L3 are fairly overlapped along the neutral line *nl1*, we

cannot tell definitely whether the free energy concentration is actually occurring along the interface between L1 and L3 or along the strongly sheared loop L3. Nevertheless, in either case, although the energy transfer from the loop top, where the initial instability was triggered, to the foot regions cannot be excluded, the fundamental energy release in this flare, especially after the onset, should be taking place at the sites of free energy concentration (Machado et al. 1988; Low & Wolfson 1988). Particularly, one such site is the foot A, which is also the locus of the strong concentration of magnetic longitudinal flux, vertical current and free energy, and the other site is B, located over the reverse line of magnetic longitudinal field and vertical current, where strong nonpotentiality is dominant and the separatrix layer may be involved in the energy release (Wang 1997; Wang et al. 1997).

A distinctly different case is seen for the pattern L2, which fairly deviate from the free energy concentration around *nl2*, implying that the flaring of L2, unlike L3, could be a secondary effect of energy transfer from the initial flaring site. We are encouraged to hold that a certain energy flux, most possibly through thermal conduction, from the flaring loop L3, was input along the loop L2 and impacted on region C, noting that the gradual radiation behavior and special H_α spectral feature in the region C support this idea (Qiu et al. 1997).

From above, a schematic interpretation of the trigger and energy release in the flare on October 27 is shown in the cartoon in Fig.6.6.

6.3.4 Energy Budget

Based on the physical quantities analyzed in Qiu et al. (1997), we can estimate the energy of the flare in both the thermal and nonthermal senses. The time variation of the GOES SXR power is integrated in time as the thermal energy released in the flare, which amounts to 3×10^{29}erg in about 30 minutes. Taking the nonthermal flux as 10^{10}erg cm^{-2}s^{-1} and considering that the nonthermal electrons deposited in the areas of about two times $3''\times3''$ (Qiu et al. 1997) lasting for one minute, we obtain the nonthermal energy, carried by the electron beams and transferred to the lower atmosphere, as 6×10^{28}erg. There could be overlapping between the nonthermal energy calculated above and the thermal energy estimated from GOES emission, but as a rough idea, more thermal energy is involved in this flare and up to several times 10^{29}erg energy is released in this single flare.

The total free energy associated with this event is estimated in an e-fold decaying field above the photosphere, in the region framed in Fig.6.5. A height of 1000km is taken into consideration and the free energy stored in such layer is obtained as 2.3×10^{31}erg, equivalent to the energy in a depth of 430km with the photospheric energy density above the contour level of 1.5×10^{5}erg cm^{-3} (Fig.6.5). It is comprehensible and generally accepted that the burst of an even important flare is far less energetic than enough to drain up the free energy at one go. Instead, the global configuration in this active region is hardly changed on this day and has produced several important (including homogeneous) flares in the zones of magnetic complexity, which is, however, beyond the scope of the present paper.

6.4 Conclusion

In this paper, we investigate the evolution of the magnetic configuration in a famous active region (AR7321) from October 26 to October 27, just on the eve of the occurrence

of a 1N/M1.1 flare. The vector photospheric magnetograms are exploited to recover the comprehensive magnetic connectivity patterns and the vertical current system, which are confirmed to bear close spatial correlation with the configuration of the flare observed in different wavelengths displaying the phenomenon from the chromospheric to the coronal level. With these results, we explore the magnetic configuration for the trigger and free energy release in the flare. Our main conclusions are summarized as follows:

The active region is typical of continuous and vehement flux emergence which accounts for the greatly enhanced nonpotentiality in this region; specifically, a newly emerging bipole on Oct. 27 along the neutral line brings in strong shear and possibly carries the horizontal current. This low-lying, strongly sheared loop (L3) pushes a pre-existent overlying loop (L1) and strong free energy, up to 10^{31}erg, is accumulated along this zone of magnetic complexity.

We employ the filtering technique on the observed raw photospheric magnetograms to obtain the improved vertical current distribution in this active region. It is found that the major current pairs were born associated with the emerging flux and the strong current concentrations were located near the most active emerging poles. Some of the flare kernels show close spatial relationship to the strong current concentration sites. One loop (L1) can be approximately identified as carrying the field-aligned current with both feet rooted in the vertical current concentration sites in the photosphere; while the low-lying loop L3 straddles almost parallel to the magnetic neutral line and current reverse line, one end (A) anchored on the edge of the vertical current maximum, and the other end (B) plunging into the reversing zone of longitudinal field and vertical current, closely associated with the separatrix, or interface, between the two magnetic structures.

The magnetic connection patterns, deduced from the photospheric vector field, are identified in the space by the flare configuration in multi-waveband observations, and can thus be supposed as magnetic loops projected into the photosphere. We find clear evidence in the observations that the flare is initiated by the interaction between the two loops L3 and L1, on the top (D) of L3, and further energy release is triggered along the L3 loop, especially at the foot regions of A and B. All three bright locus seen in SXR images from the onset to the impulsive phase of the flare are well coaligned with the concentrations of the free magnetic energy, ie., the excess magnetic energy of the observed field to that of a potential field and the ways to release the free energy in these three regions may differ according to their local physics.

Subsequently, the flaring of another region (C) doesn't go along the free energy concentration zone but appears a secondary effect from the initial flaring site (loop L3) through the transfer of energy flux. The above scenario of the flare is supported by the previous studies of the same event.

Figure Captions

Fig. 6.1. The photospheric vector magnetograms (contours) taken on (a) Oct. 26, 03:34UT and (b) Oct. 27, 01:44UT superposed on the white light images showing the spots. The white contours in both figures demonstrate the intensity of the longitudinal field (levels = $\pm$500, 1500, 2500, and 3500 Gauss); solid lines show positive field and dashed lines show the negative field. The short arrows indicate the transverse field; the length of each arrow gives the magnitude of the field and the arrow gives the direction. The longitudinal inversion line is plotted in thick dark lines and the grey, thick curves indicate the magnetic

connection patterns (see the text). The field of view (FOV) is $170'' \times 170''$.

Fig. 6.2. Vertical current distributions on (a) Oct. 26 and (b) Oct. 27 with the magnetic longitudinal field superposed on (solid and dashed contours). The bright (dark) color indicate the current flowing out of (into) the photosphere, or upward (downward). The grey scale at the bottom gives the intensity of the current and the levels are -2.4, -1.8, -1.2, -0.6, 0, 0.6, 1.2, 1.8, 2.4×10^{-2}A/m^2 from dark to bright colors. The magnetic longitudinal inversion line is drawn in white, thick lines in both figures. The FOV is the same as that in Fig. 6.1.

Fig. 6.3. The magnetic longitudinal field (contours) on Oct. 27, 01:44UT superposed on the SXR images (grey map) on (a) Oct. 27, 01:44:33UT and (b) Oct. 27, 01:45:31UT taken by *Yohkoh* SXT from the filter Al.1. To illustrate clearly the structures at different times, the two SXR images are not shown in the same grey scale. The contour levels are the same as in Fig. 6.1. The thick dark line indicates the longitudinal field inversion line. In (b), the H_β flare kernels (01:55:26UT on Oct. 27) are plotted in thick grey contours. The field of view (FOV) is $160'' \times 160''$.

Fig. 6.4. The coalignment of SXR images on (a) Oct. 27, 01:44:33UT, (b) Oct. 27, 01:45:31UT taken by *Yohkoh* SXT from the filter Al.1 with the vertical current distribution (contour) on Oct. 27, 01:44UT and with the magnetic connection patterns (thick grey curves). The solid (dashed) lines represent the current flowing out of (into) the photosphere. The contour levels of both figures are ± 0.6, 1.2, 1.8, 2.4 $\times 10^{-2}$A/m^2. In both figures, the longitudinal inversion line is drawn in thick dark line and the current reverse line in thick grey line. In (b), the H_β flare is overlapped in thick grey contours. The FOV is the same as that in Fig. 4.3.

Fig. 6.5. The distribution of magnetic free energy (contour) superposed on the SXR image on Oct. 27, 01:44:33UT UT taken by *Yohkoh* SXT from the filter Al.1. The magnetic patterns are also shown in grey curves and the magnetic inversion line is draw in thick dark line. The dashed-line frame gives the area taken to calculate the total free energy in the flare (see the text). The contour levels are 1.5, 2.5, 3.8, 5.0 $\times 10^5$erg cm^{-3}. The FOV is the same as that in Fig. 6.3.

Fig. 6.6. The schematic interpretation of the flare configuration on Oct. 27.